[UCI]I804:24011-200000240200

2010 년 8 월

석사학위논문

실내용 가시광 통신 시스템 시뮬레이션 연구

Simulation of indoor visible light communication system

조선대학교 대학원

전자공학과

응구엔쾅후이

실내용 가시광 통신 시스템 시뮬레이션 연구

Simulation of indoor visible light communication system

2010 년 8 월 25 일

조선대학교 대학원

전자공학과

응구엔광후이

실내용 가시광 통신 시스템 시뮬레이션 연구

Simulation of indoor visible light communication system

지도교수 이 충 규

이 논문을 전자공학 석사학위신청 논문으로 제출함

2010 년 5 월

조선대학교 대학원

전자공학과

응구엔쾅후이

응구엔쾅후이의 석사학위논문을 인준함

위원장 조선대학교 교수 김정화 (인)

위원 조선대학교 조교수 강문수 (인)

위원 조선대학교 조교수 이충규 (인)

2010 년 5 월 일

조선대학교 대학원

Contents

초 록

실내용 가시광 통신 시스템 시뮬레이션 연구

응구엔 광 후이

지도 교수 : 이 충 규

조선대학교 대학원 전자공학과

실내 가시광 통신은 많은 통신 방법들 중 하나이다. 최근 수 십년동안, LED (Light Emitting Diode)를 이용한 통신 시스템이 연구되었다. 이것은 미래 발전을 위한 매우 획기적인 것이다. LED 는 저전력 소자이고 단가가 매우 저렴하며, 밝은 광도를 낼 수 있기 때문에, 이러한 장점을 구비한 LED 를 사용함으로써, 사람들은 전력 및 에너지에 관한 많은 문제를 해결할 수 있을 것이다. 최근 유럽 및 일본을 중심으로 한 연구팀들이 이러한 조명용 LED 를 조명용 광원 뿐만 아니라 통신 모듈로 이용하여 실내 무선 통신 시스템에 적용하기 위한 연구들이 수행되고 있다.

본 논문에서는 보다 더 현실적으로 LED 를 이용한 실내 가시광 무선통신 시스템의 성능을 향상시키기 위한 연구를 위한 시뮬레이션 프로그램을 MATLAB 및 Simulink 소프트웨어를 사용하여 개발한다. 이것은 각각의 장애물인 벽에 의한 반사성분과 송신기의 위치에 관하여 기본적으로 고려한다. 송신기의 위치와 반사 값에 관하여 Lambertian 패턴 효과를 가정하여, 광파워 분포 및 RMS delay spread 등에 대한 분포특성을 보여준다. 시뮬레이션 프로그램을 사용함으로써 광분포와 RMS delay spread 는 바닥 표면에서 분석된다.

데이터 전송 또한 데이터 변조에 따른 파형계산과 잡음성분, 반사성분, 광학필터 등 실내 가시광 통신을 위해 가정된 요소들을 고려하여 시뮬레이션 프로그램을 개발한다. MATLAB 및 simulink 에 의한 이 시뮬레이션 프로그램은 실내 가시광 통신을 위한 데이터 전송 상태와 결과를 통해, 실내 가시광 무선통신 시스템 실험을 위한 설계과정에 중요한 역할을 할 수 있을 것으로 기대한다.

ABSTRACT

Simulation of indoor visible light communication system

Nguyen, Quang Huy

Advisor : Prof. Lee, Chung Ghiu, Ph.D.

Department of Electronic Engineering,

Graduate School of Chosun University.

Visible light communication is one of a new way for communication. In recent decades, communication using Light Emitting Diodes (LEDs) was studied, and it was immediately auspicious for many developments in the future. Using LEDs, people can solve many problem relate the investment of power, saving the energy, high properly, commercial and safe for human. Nowadays, in the wireless communication system for indoor environment, LEDs is used not only as a lighting device, but also as a communication device.

For improving the system of wireless indoor using LEDs more and more realistic, in this thesis, I report a simulation program for indoor visible light communication environment based on MATLAB and Simulink. The program considers the positions of the transmitters and the reflections at each wall. Assuming the effect of Lambertian pattern at the transmitters and reflected points. Some results can be compared with research of Prof. Nakagawa and will show a deeply effects of Lambertian pattern at reflected point. By using the simulation program, the distributions of illuminance and root-mean-square delay spread are analyzed at bottom surface.

A data transmission is also simulated by using all of assumption parameters for indoor communication such as: data modulation format, noise, reflection modeling, optical filter …The dynamic simulation program supported by Matlab/simulink was made to show the operation of data transmission for indoor communication system.

Chapter 1

INTRODUCTION

Wireless communication is one of the most vibrant areas in the communication fields today. With the development over a hundred years, wireless technology marked many achievement of human. The remarkable things are photophone, radio, wireless network; other kind is optical wireless such as: infrared, laser and visible light communication which can be named by free space optical communication.

Traditionally, radio frequency transmission was used in wireless applications. However, the RF spectrum is so congested that it is very difficult to accommodate high bit rate applications. The optical systems with low implementation complexity and no spectrum license requirements provide a possible solution. The optical infrared energy can typically confine within the communication environment. This eliminates the problems of interference generated by neighboring users and offers a degree of security at the physical layer level. The transmission equipment and optical wavelength can be reused at other parts of the building. Optical wireless systems also offer immunity from signal fading, which is a major problem in RF communication systems. As such, indoor infrared communications has gained importance, especially in view of the increased data mobility requirements of users for both computing and communications.

Infrared communications were mainly studied during 1960’s as an alternative for mobile radio communications. The optical infrared energy can typically confine within the communication environment. This eliminates the problems of interference generated by neighboring users and offers a degree of security at the physical layer level. Infrared has gained ground with operators seeking to cover area that require high bit rate services such as the office areas. It was a very rapidly developing research and there was huge interest and commitment in this area by major communication industries due to its enormous commercial applications.

In recent decades, the wireless indoor communication system using LEDs is the fresh field. Using LEDs, There are a lot of advantages when comparing with another ways of wireless communication:

- Lighting equipment with LEDs is easy to install, nice looking and safe for human eye.
- For commerce, low cost and long life expectancy are the considerable advantages.
- Satisfying at high data rate communication and low power consumption are the indispensable characteristics for the trend of globalization about saving energy in the future.

The main problems of wireless communication using LEDs are studied and solved by many labs in the world: optical link, path lost, multi-path, BER (bit-error-rate), SNR (Signal to Noise Ratio), shadowing…

In near future, the applications of the wireless communication indoor using LEDs will be used at anytime and anywhere. Thus, the trend of development of communication technology is that how to make this more and more realistic.

The most of the contents are the research results of the ETRI project [41]. This thesis deals mainly with the study of the performance of LEDs characteristics for indoor communication. The main objectives of the work are discussed in the following section.

1.1. Thesis objectives

In this thesis, I propose a simulation model for an optical wireless communication system; the simulation program was developed similar to the previous research of Prof. Nakagawa. The developed software was used to survey the wireless indoor communication system.

- To study the effect of illumination with the Lambertian pattern at the reflected point on the wall.
- To analyze the effect of emission LEDs to achievable data rate.
- To show a way for simulating communication system by MATLAB/Simulink.

1.2. Thesis organization

Chapter 2 gives a review of optical communication. The basic components of optical communication and challenging are discussed. Chapter 3 summarizes the visible light communication indoor using LEDs. Chapter 4 deals with simulation studies of LEDs emission pattern and simulating a communication system using MATLAB/Simulink. The results are also discussed. Chapter 5 presents the conclusions of the work.

Chapter 2

REVIEW OPTICAL COMMUNICATION

2.1 Visible light communication

Since the effect of optical communication was proved, it showed many advantage when comparing with the previous technique. Table 1 shows the comparison between optical communication and RF techniques.

	Optical wireless		rf	
	Visible light	IrDA	UWB	Wireless 1394
Data rate	>100 Mb/s possible	4, 16 Mb/s	~500 Mb/s	40 (>100)Mbps
Distance	~meters	~3 m	~meters	~10 to ~20 m
Application	Ubiquitous network	IrDA application including remote controller	Personal area network	Home appliances, mobile terminals
Security	Good	Good	No	No
Wavelength	450 to 650 nm visible light	850 to 900 nm infrared	3 to 10 GHz rf	5.2 GHz (25, 40, 60 GHz) rf
Service	Communication, illumination	Communication	Communication, positioning	Communication
Noise source	Sun light	Ambient light	Other user	Other user
Environmental	Eye safe	Eye safe	EMI	EMI
Regulations	No	No	Exist	Exist

Table 1: Comparison between optical and RF communication techniques. [3]

Visible light communication is suitable for low to medium bit rates. The most common application for free space optical communication is the remote control of consumer applications such as stereos and television sets. Other applications are the remote control of automobile door locks and the cordless interface between computers and peripheral devices such as a mouse, keyboard and printer.

In the first time, it was limited to line-of-sight applications since obstacles such as walls and floor will block the path of light. Furniture may also block the path of light. However, a light beam may be reflected from the ceiling so that communication may still be possible even if there is no direct line of sight connection between the optical transmitter and the receiver.

If we restrict our considerations to small distances, the transmission medium air can be considered to be totaled lossless. However, the optical signal strength decreases for un-collimated light beams due to spatial divergence. For isotropic emitters, the intensity decreases with the square of the radius.

$$I = P/(4\pi r^2) \quad (1)$$

Where P is the optical power emitted by the source and r is the distance from the source. The decrease in intensity thus has a very different dependence compared with the intensity in fiber communication.

The rapidly decreasing intensity limits the maximum range of optical communication. Collimated light beams can overcome this problem. Transmission distances of several km are possible without significant loss provided that atmospheric conditions are good, for example in the absence of fog or predication. Semiconductor lasers are used for such collimated transmission system due to the ability to form collimated beams with very little spatial dispersion.

Multipath distortion or multipath time delay severely limits the date rate in these communication systems. A schematic illustration of multipath distortion is shown in Fig. (1). A light beam emanating from the optical transmitter may take several different paths from the transmitter to the receiver. This is especially true for rooms with high-reflectivity surfaces such as white ceilings, walls, or mirrors. As an approximate rule, the longest path is assumed to be twice as long as the shortest path between the transmitter and the receiver. This approximate rule leads to a multipath distortion time delay of

$$\Delta\tau = L/c \quad (2)$$

Where L is the transmitter-receiver distance and c is the velocity of light. The maximum data rate is then limited to

$$f_{max} \approx 1/\Delta\tau \quad (3)$$

For a room size of 5m, the multipath delay is about $\Delta\tau$ = 17ns. Thus the data rate will be limited to about 60 MHz.

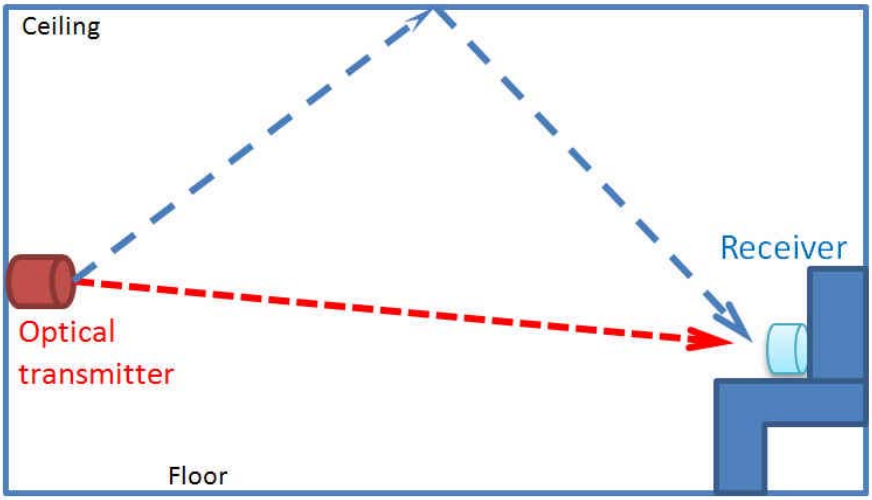

Fig.1: Illustration of multipath distortion of a free-space optical signal which limits the maximum data rate of the signal.

Another limitation of optical communication is the detector noise. Sunlight and incandescent light source have strong emission in the infrared. Thus the large DC photocurrent is generated in the detector, especially under direct sunlight condition. The detector noise can be reduced by limiting the bandwidth of the receiver system. By reducing the bandwidth of the receiver system, and thereby also the system data rate, the detector noise is reduced, since the noise spectrum is much wider than the system bandwidth.

The detector noise due to ambient light sources can also be reduced by using optical band pass filters, long-wavelength-pass filters, or a combination of both filters. Such filters prevent unwanted ambient light from reaching the detector.

2.2 Indoor wireless system

A block diagram of a typical indoor optical wireless system is illustrated in Fig (2)

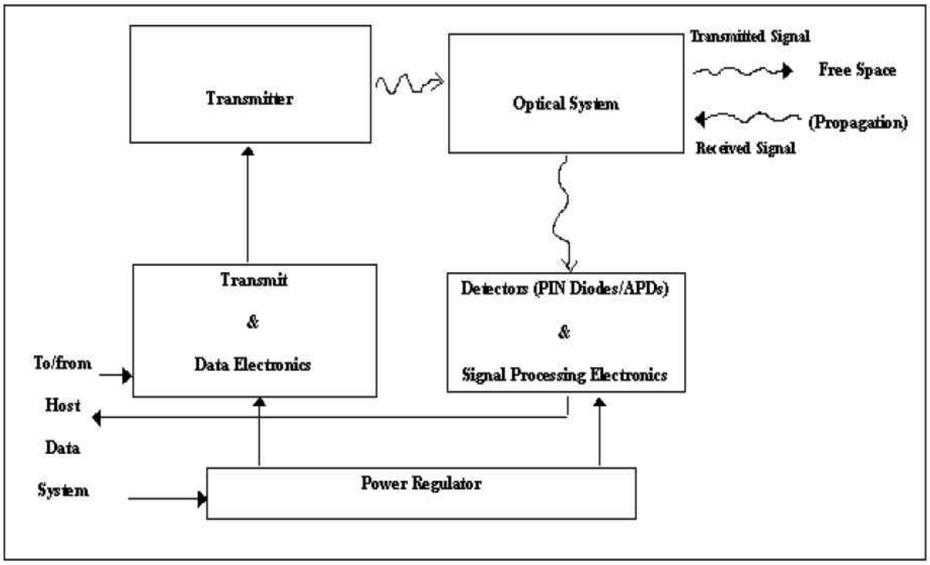

Fig. 2: A block diagram of a typical indoor optical wireless system. [3]

A basic optical wireless system consists of a transmitter (using LEDs or LDs), free space as the propagation medium and the receiver (using APDs or PIN diodes). Information, typically in the form of digital data, is input to electronic circuitry that modulates the transmitting light source (LEDs/LDs). The source output passes through an optical system (typically has telescope and optical diplexer) into the free space (propagation medium). The received signal also comes through the optical system and passes along the optical signal detectors (PIN diodes/APDs) and thereafter to signal processing electronics.

In the past, the development for optical indoor communication used Infrared was studied. The wavelength band from 780 nm to 950 nm was the good candidate for indoor system. In this range, low cost LEDs and LDs are readily available. Also, this band coincides with the peak responsively of inexpensive, low-capacitance silicon photodiodes. The optical wireless system uses IR technology in which links are based on intensity modulation and direct detection (IM/DD) of the optical carrier. Intensity modulation is performed by varying the drive current of LED or LD (direct modulation). Direct detection is performed by PIN photo-diodes or APDs which produce an electric current proportional to the incident optical power.

Nowadays, by the development of technology, using the visible light with the wavelength of range from 375 nm to 780 nm is studied. First applications are published, for example the transmission audio signal, video signal, control and network applications. The term of visible light communication will be able to get the high commercial.

2.2.1 Transmitters

There are several kinds of transmitters using Laser Diodes (LDs), Infrared (IR) and LEDs for visible light. For indoor optical wireless transmitter, LDs are preferable over LEDs because they have higher optical power outputs, broader modulation bandwidths and linear electrical to optical signal conversion characteristics. Linearity in signal conversion is particularly important when sophisticated modulation schemes such as multi-subcarrier modulation or multilevel signaling are used. But due to safety reasons (eye safety) laser diode cannot be used directly for the indoor IR systems, where radiation can enter a human eye quite easily. LDs are highly directional radiation sources and can deliver very high power within a small area on the retina thereby resulting in permanent blindness. On the other hand, LEDs are large-area emitters and thus can be operated safely at relatively higher powers. They are also less expensive and more reliable. Consequently, LEDs are the preferred light source for most indoor applications. To compensate for the lower powers, array of LEDs can be used. However, LEDs cannot be used beyond 100 Mbps due to the limitations imposed by the mechanism by which they emit light, whereas LDs can be used for transmission at bit rates of the order of a few Gbps. A comparison between LEDs and LDs is shown in Table 2 [33].

Characteristic	Light-Emitting Diodes	Laser Diodes
Spectral Width	25 to 100 nm (10 to 50 THz)	$<10^{-5}$ to 5 nm (<1 MHz to 2 MHz)
Modulation Bandwidth	Tens of KHz to tens of MHz	Tens of MHz to tens of GHz
E/O Conversion Efficiency	10 to 20%	30 to 70%
Eye Safety	Generally considered eye-safe	Must be rendered eye-safe, Especially for $\lambda < 1400$ nm
Cost	Low	Moderate to high

Table 2: Comparison between LEDs and LDs. [33]

2.2.2 *Propagation medium*

Like any wireless system, the link power budget for an optical wireless system is strongly dependent on atmospheric loss along the path of the propagation. Since indoor atmosphere is free of environmental degradation, such as mist, fog, particulate matter, clouds etc., indoor optical wireless systems encounter only free space loss and signal fading.

Free Space Loss: It is that part of the transmitted power, which is lost or not captured by the receiver's aperture (Fig. 3). A typical figure for a point-to-point system that operates with a slightly diverging beam would be 20dB, whereas an indoor system using a wide-angle beam could have a free space loss of 40dB or more [33].

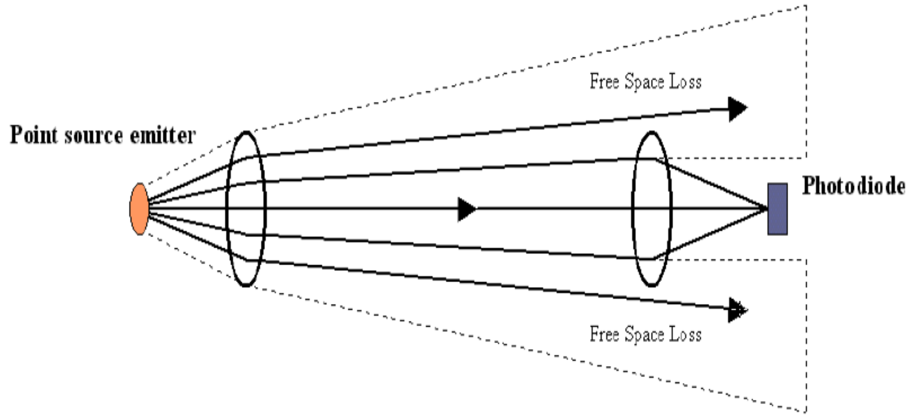

Fig. 3: Free Space loss.

Signal Fading: This can be observed in both indoor and outdoor optical wireless systems. The reason for this is reception of signals via different paths by the receiver. Some of these interfere destructively (i.e. they are out of phase); so that the received signal power effectively decreases. This type of degradation is also known as multi-path signal fading.

2.2.3 *Receivers*

As mentioned earlier, there are two basic detectors; the PIN diodes and the APDs. PIN receivers are commonly used due to their lower cost, tolerance to wide temperature fluctuations and operation with an inexpensive low-bias voltage power supply. PIN receivers are about 10 to 15 dB less sensitive than APD receivers. Increasing the transmitter power and using larger receiver lens diameter can compensate the reduced sensitivity of these receivers. On the other hand, the increased power margin afforded by the APDs provides a more robust communication link, which reduces the criticality of accurate aiming of lenses. This allows in reduction of transmitter power. In addition to this, the better internal gain of APDs increases the Signal-to-Noise Ratio (SNR). However, the APD receivers are costly and need high operating voltages.

2.3 Transmission techniques

Several transmission techniques are possible for indoor optical wireless systems; these techniques may be classified according to the degree of directionality of transmitter and receiver [4]. A transmitter and receiver may have a narrow or broad radiation pattern or field of view (FOV) and can be combined to make directed, non-directed, or hybrid systems (Fig.4).

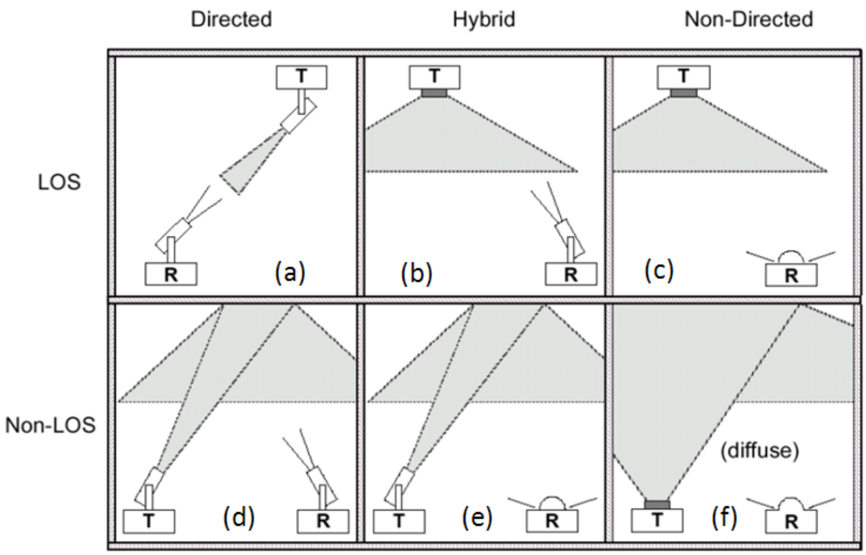

Fig.4: Classification of simple optical link according to the degree of directionality of the transmitter and receiver and whether the link relies upon the existence of a LOS path between them. [4]

In general, the model architecture provides a compromise between the directed radiation and diffuse radiation options. The transmission techniques may also be classified as line-of-sight (LOS) or non-line-of-sight (non-LOS) depending on whether or not, they rely on the existence of a directed path between transmitter and receiver [4]. Fig. 4 shows all the possible configurations for LEDs transmission. In the cases (a), (b) and (c), the transmitter (T) and receiver (R) are in transmit-LOS mode. The beam can travel directly from the transmitter to the receiver, without reflection. In cases (d), (e) and (f) there is no direct path and before reaching the receiver, the signal is reflected by the ceiling and walls.

The two most common configurations are directed-LOS systems and non-directed non-LOS systems. Non-directed non-LOS systems are commonly referred to as diffuse systems. In general, directed LOS links minimize path loss and maximize power efficiency, and they can achieve higher transmission rates. However, such systems require careful aiming and are not capable of supporting one-to-many and many-to-one connections. Furthermore, shadowing can significantly degrade such systems. While supporting lower transmission rates, non-directed non-LOS (diffuse) systems have increased robustness against shadowing and provide ease of use, allowing high user mobility. They also allow links to operate even when barriers are there between the transmitter and receiver [4].

2.3.1 Directed beam radiation

The optical beam travels directly without any reflection from the transmitter to the receiver. The optical wireless link using this technique is established between two fixed data terminals with highly directional transmitter and receiver at both ends of the link. As there is no mobility, the beam aperture angle and the FOV of the transmitter and the receiver respectively can be reduced. As a result, this technique minimizes path loss and maximizes power efficiency and systems using this technique can achieve higher transmission rates. The main drawback of this technique is the lack of mobility, and susceptibility to blocking by personnel and machines. The narrow beams also create pointing problems. The beam-width should be chosen such that any inexperienced operator should be able to manually aim the transmitter towards the receiver unit.

2.3.2 Diffuse radiation

The transmitters send optical signals in a wide angle to the ceiling and after one or several reflections the signals arrive at the receivers. This is the most desirable configuration from a users’ point of view, since no alignment is required prior to use, and the systems do not require a line-of-sight path for transmission. However, systems using this technique have a higher path loss than the directed radiation counterparts, requiring higher transmitter power levels and receivers with larger light collection area. Another challenging problem in this technique is the multipath dispersion. When a short duration pulse is transmitted in a wide angle, it travels through multiple paths, resulting in a broadened pulse. This effect is known as multipath dispersion. This causes inter-symbol- interference (ISI) at higher data rates or in larger cell system [33]. In this configuration, the data rate depends on the room size and the reflection coefficients of the surfaces inside the room.

2.3.3 *Quasi-diffuse radiation*

There is a base station (BS) with a relatively broad coverage made of passive or active reflector. The BS is usually mounted on the ceiling. The BS transmits (receives) the signal power to (from) the remote terminals (RTs). In a link between any terminal and the BS, the line of sight always must be maintained. Consequently, the RTs cannot be fully mobile. The RT's transceiver must be aimed to the BS, or its FOV must be wide enough to enable communication between itself and the BS from any position in the room. In another form of this technique, the transmitter may send the optical signal to a designated area on the ceiling and the receiver is supposed to face that area.

Chapter 3

VISIBLE LIGHT COMMUNICATION INDOOR USING LEDs

A part of the results described here is in preparation for a technical journal.

3.1 Physical modeling, parameters

Assuming a typical office room size is 5m x 5m x 3m; the LEDs are installed on the ceiling; the height of desk is 0.85m and the terminal is put on the desk. The characteristic of the system is given by Table 4:

Semi-angle at half power	70[deg]
Center luminous intensity	0.73[cd]
Number of LED each group	3600 (60x60)
Transmitted optical power	20 [mW]
Detector physical area of a PD	1[cm^2]
Field of view	60[deg]
Reflection coefficient	0.8

Table 4: Simulation parameters.

To study the effect of LED emission pattern with non-circular cross-section on both illumination and communication, a typical office room with the dimension of 5m × 5m × 3m is assumed. Also, the optical wireless communication link is assumed to be line-of-sight (LOS) diffuse link [4]. It is assumed that the LED lamps are installed at a height of 3 m from the floor and the receiver is placed at the height of 0.85 m. The received optical power at the receiver is composed of two components. One is directed from the light and the other is reflected from the walls. For the case of multiple transmitters, we assume the transmitters to emit equal powers.

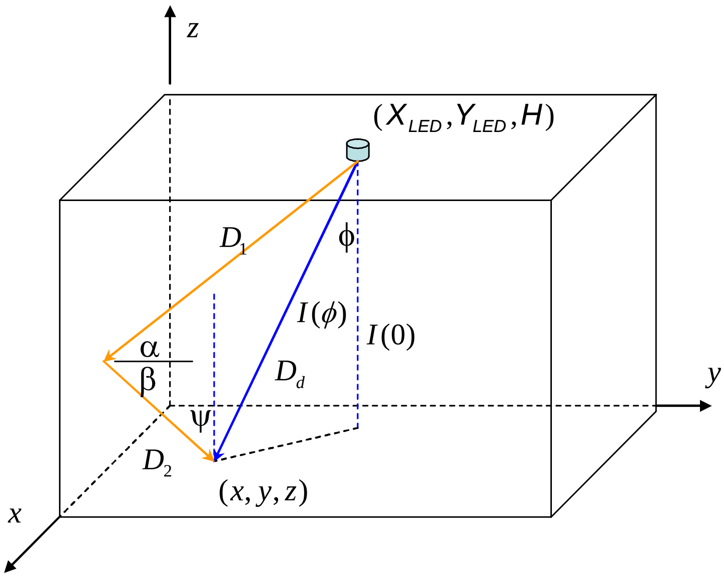

Fig. 5: Geometrical configuration for simulation.

Fig. 5 depicts a geometrical configuration for simulation of the paper considering the first reflection components. The mathematical expressions for illumination are described in [4]. $I(\phi)$ is the luminous intensity in the angle of irradiance ϕ, and $I(0)$ is the center luminous intensity of an LED light approximated from a group of LEDs, ψ is the angle of incidence to the receiver. α is the incidence angle at a reflection point and β defines the angle from a reflection point to a specific receiving point. D_1 is the distance between the source and a reflection point, D_2 is the distance between the reflection point and a receiving point. D_d is the distance between a center of group of LEDs and a receiver. A horizontal illuminance E_{hor} at a point (x, y, z) on a receiving plane is calculated from the following equation (4),

$$E_{hor}(x, y, z) = \frac{I(0)\cos^m(\phi)}{D_d^2 \cdot \cos(\psi)} \tag{4}$$

Where m is the order of Lambertian emission, which is given by $m = -\ln 2 / \ln(\cos\phi_{1/2})$, where $\phi_{1/2}$ is the semi-angle at half power. The semi-angle at half power is defined as the viewing angle when the irradiance is half of the value at 0 degree.

Nakagawa et al. approximated an LED lighting composed of 3600 LEDs to one LED with equivalent total optical power for calculation of illuminance distributions from the above equation for horizontal illuminance [17]. Nakagawa also assumed having the Lambertian pattern at the transmitters. However, in the realistic case, for example, if the surface of the wall is not smooth or there is something on the wall such as water, liquid…it maybe makes the dispersion of the coming light. Thus, in this thesis, the ideal about the dispersion at the reflected point also has a Lambertian pattern is assumed and simulated.

Although a practical LED lamp may be composed of many LEDs, it can be approximated to an LED with equivalent optical power for simplicity in calculation [11, 16 and 17]. To model a cluster of LEDs as a directional point source according to the LED radiation pattern, arrangement of LEDs, and the number of LEDs, the far-field condition and the precise optical model of LED radiation have been reported in [22]. Here, we treat individual LEDs in an array as point sources because their dimension is small enough compared to the distance from the LEDs to the receiver, i.e. they are in the far-field condition.

To survey the Illuminance distribution of LEDs system, we assume some kinds of configuration for position of the LEDs on the ceiling. In case of 1 transmitter, the position is the center of the ceiling, and for 4 transmitters the transmitters are located at the position like Fig.6

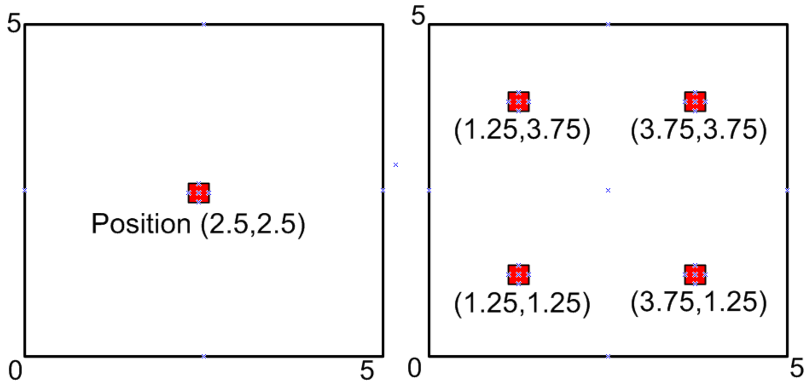

Fig.6: position of transmitters in case 1 and 4 groups on the ceiling.

3.2 Discussion on Multiple wavelengths in VLC

We have assumed that the LED emits a monochromatic light. The optical power [Watt] of monochromatic light is related to the illuminance through a constant and is expressed as the function:

$$P_{dir} = \frac{I(0)\cos^m(\phi)}{683V(\lambda)D_d^2\cos(\psi)} \tag{5}$$

$V(\lambda)$ is the eye sensitivity function [29]; the conversion between radiometric [Watt] and photometric unit [lx] is given by:

$$Photometric\ unit = radiometric\ unit \times 683\left(\frac{lm}{W}\right) \times V(\lambda) \tag{6}$$

According to [29], at the wavelength of 555 nm (green color), we have the eye sensitivity $V(550\ \ nm) = 1$; and at the wavelength of 720 nm (red color), the eye sensitivity $V(720\ \ nm) = 0.001$. It proves the numerical calculation in the section 5.2.

However, the illumination LED provides the multiple wavelengths in visible range, for example, 300 nm ~ 780 nm. Therefore, the calculations of the illuminance and received optical power involve the integration over wavelengths occupied by the light and passed by the receiver optical filter.

$$P_{dir} = \frac{I(0)\cos^m(\phi)}{683 D_d^2 \cos(\psi) \int_{300}^{780} V(\lambda) P(\lambda) d\lambda} \qquad (7)$$

$P(\lambda)$ is the power spectral density [29].

Also, the multiple wavelengths can scatter at different angles upon reflecting at rough wall surfaces. Additionally, the optical lens used in concentrator or photodetector would introduce aberration. These effects would contribute to increase in the RMS delay spread and, consequently, to limit the maximum data rate. It is expected that the proposed model will be improved by adding the simulation models for multi-wavelength LEDs and wavelength-dependent reflection coefficients at wall surfaces.

Including the reflection light, the function of the optical power becomes:

$$P_{total} = \sum^{LEDs} \left\{ P_{dir,\lambda} + \sum_{j}^{N} P_{ref,\lambda,j} \right\} \qquad (8)$$

3.3 Ongoing research on the world

The main problems of wireless communication using LEDs are studied and solved by many labs in the world: optical link, path lost, multi-path, BER (bit-error-rate), SNR (Signal to Noise Ratio), shadowing… I specified in here some main problem as a trend to development for LEDs communication.

3.3.1 Increasing data rate

Perhaps the simplest way of mitigating the low bandwidth of the transmitter is to block the phosphor component at the receiver by using a blue filter. In [34] it is shown that this can increase the bandwidth substantially, albeit at the penalty of a small reduction in received power due to filter losses. It is also possible to improve the response by transmitter and/or receiver equalization, or the use of bandwidth-efficient modulation schemes that take advantage of the high available signal to noise ratio. In addition, for higher data rates it may be possible to use parallel data transmission from a number of LEDs. Each of these techniques is discussed in more detail below.

A. Transmitter equalization

Analogue equalization techniques can be used to compensate for the rapid fall-off in response of the white LEDs at high frequencies. It is possible to use an array of LEDs, each driven using a resonant technique with a particular peak output frequency to achieve this. Careful choice of a number of different frequencies allows the overall response to be 'tuned' to that desired. In [26] a 16 LED array is modified to have a bandwidth of 25MHz (without blue filtering) offering a data-rate of 40Mb/s for Non-Return to Zero (NRZ) On-Off Keying (OOK). More complex equalization can also be used for single devices, and data rates of 80Mb/s (NRZ OOK) [35] have been demonstrated.

B. Receiver equalization

Transmitter equalization has the disadvantage that the drive circuits for the LED (which often involve currents of several hundred milliamps) need modification, and in a typical coverage area there may be a number of sources, making the modifications potentially costly. In addition some of the signal energy used is not converted into light, thus reducing the energy efficiency of the emitter. Equalization at the receiver allows complexity to be at the receiver only. A simple first-order analogue equalizer is modeled in [36], and this shows there is substantial improvement in data-rates. More complex approaches are likely to yield higher data rates.

C. Complex modulation

A high-SNR, low-bandwidth channel is typically suited to high bandwidth efficiency multilevel modulation schemes. Work in [34] shows that 100Mbit/s is possible using Discrete Multi-Tone Modulation (DMT). At present there is little work in this area, and further studies are required in order to assess the relative benefits of analogue equalization with relatively simple modulation, or complex modulation and limited channel bandwidth.

D. Parallel communication (Optical MIMO)

In most illumination applications many LEDs are used to provide the necessary lighting intensity. This offers the opportunity of transmitting different data on each device or on different groups of emitters. For this to be successful a detector array is required at the receiver, and this creates a Multi-Input Multi-Output (MIMO) system. Radio-frequency MIMO techniques can be applied to such optical transmission systems to relax the necessary alignment between the array of detectors and array of sources. Work in [26] shows that such a system can allow multi-channel data communication, without the need to align a particular detector with a corresponding source.
It can be seen that there are many different methods of increasing data rates, and that a combination of these should allow data rates well in excess of 100Mb/s to be successfully transmitted.

3.3.2 Interference

The dominant source of noise in indoor optical wireless systems is ambient light, which is typically a combination of fluorescent light, sunlight, and incandescent light. All three modes of infrared propagation suffer from the presence of ambient light. The illumination sources of indoor environments radiate in the same wavelengths as the infrared data signal. Also, typical intensity levels of the ambient light collected at the photo detector are usually much higher than data signal intensity levels. Ambient light provokes shot noise due to the random nature of the photo-detection process. Moreover, artificial light provokes interference due to periodic variations of light intensity. These variations can occur at a frequency double the power line frequency, and at the switching frequency of electronic ballasts of the fluorescent lamps. In general, for low and moderate data rates the ambient noise is the main factor degrading the performance of wireless LEDs systems [9, 10, and 11].

3.3.3 Multipath

Channel dispersion associated with multipath propagation is another major issue in indoor optical wireless systems. A multipath phenomenon occurs when the transmitted signal follows different paths on its way to the receiver due to its reflection by walls, ceilings and other objects. Multipath phenomena can cause inter-symbol-interference (ISI). Diffusive systems are more prone to multipath effects than directed beam systems. This is because of their larger beam widths leading to more potential reflectors, and the larger FOV of their detectors resulting in more reflected light being detected. As the speed of transmission increases to 10 Mbps and beyond, the ISI caused by the multipath dispersion becomes a major degrading factor.

Chapter 4

SIMULATION RESULTS

The simulation has been performed by using the simulation program developed [40] and its structure is described in section 4.2.

4.1 Circular cross section

4.1.1 Illumination of circular emission

The distribution of illuminance of our system is shown in figure below:

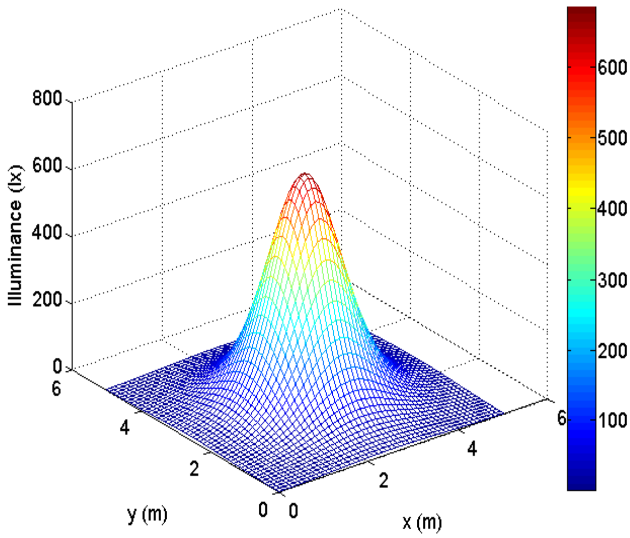

Fig. 7: the distribution of illuminance in case of 1 transmitter.
Maximum value: 683.07 lx.

Fig. 7 shows the illuminance with 1 transmitter, the semiangle at half power is 30 degree. The maximum value of luminous flux in the center is 683.07 lx. And Fig. 8 below shows the distribution for 4 transmitters with the semiangle of 30 degree. The value is in the range from 62.8 to 750.2 lx. The average value is 371.53 lx.

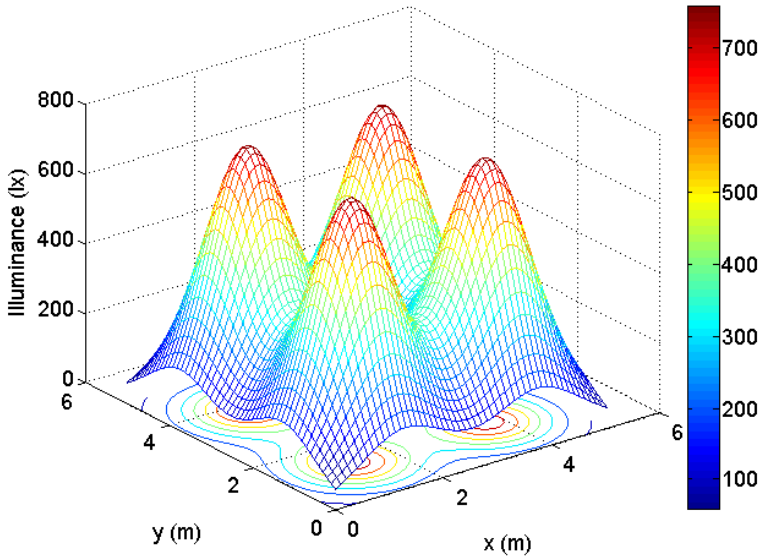

Fig. 8 a: The illuminance distribution incase of 4 transmitters
Min: 62. 8lx; Max: 750.2 lx; avarage: 371.53lx.

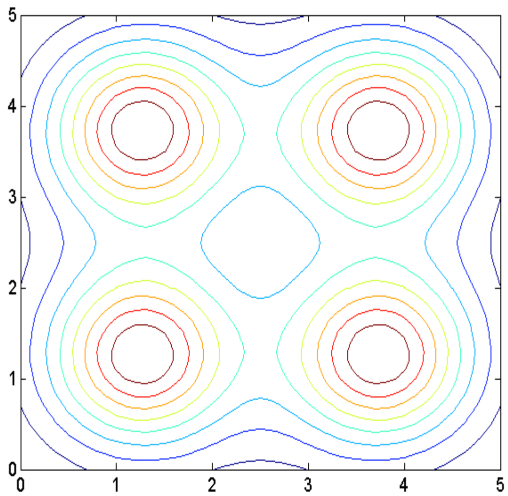

Fig. 8 b: Contour plot.

For seeing a clearly difference between our study and previous researches [14, 15], the numerical calculation in illuminace distribution of our system at the semiangle of 70 degree is shown. All of parameters are same.

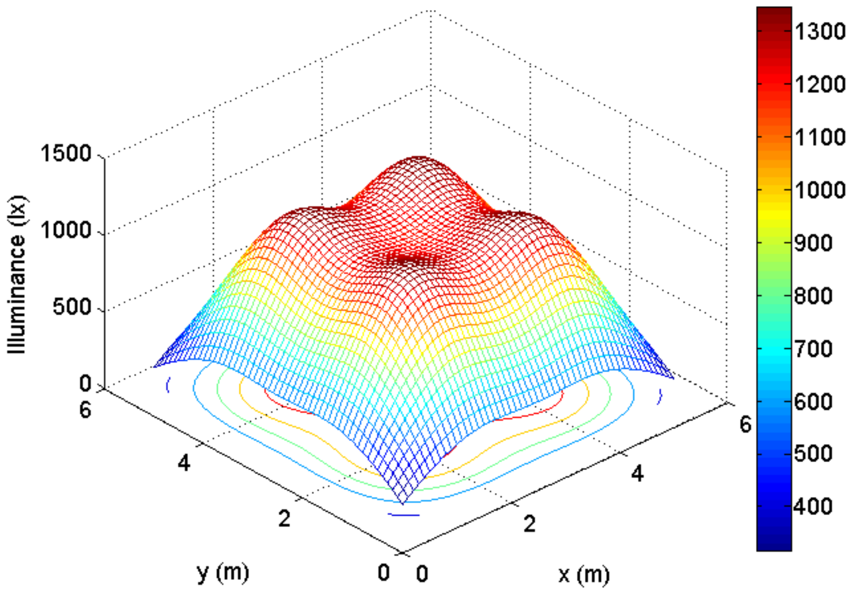

Fig. 9: The distribution of illuminance with transmitters
Max= 1342.5(lx) Min=315.9 (lx) Average=958.11 (lx).

In this case, we assume that the reflections at the reflected point have Lambertian patterns. After calculation (including direction, reflection with Lambertian pattern) and comparing with the illuminance without Lambertian pattern at reflected points, the value is larger than 10.8% (in the same conditions) in case of four transmitters.

4.1.2 Root mean delay spread for circular emission

Based on the analyses in [4,16 and 30], the channel DC gain on direct path, the optical gain for the optical concentrator, the channel DC gain, and the distributions of horizontal illuminance and received optical power are calculated. Considering both the direct path and the first reflected path, the received optical power at a point can be calculated by dividing the reflection walls into points of reflections as follows:

$$P_r = \sum^{LEDs} \left\{ P_t \cdot H_d(0) + \sum^{reflections} P_t \cdot dH_{ref}(0) \right\} \tag{9}$$

P_t is the optical power transmitted from an LED, $H_d(0)$ is the channel DC gain on directed paths [15].

$$H_d(0) = \begin{cases} \frac{(m+1)A}{2\pi D_d^2} \cos^m(\phi) T_s(\psi) g(\psi) \cos(\psi), & 0 < \psi < \Psi_c \\ 0 & \psi > \Psi_c \end{cases} \tag{10}$$

$T_s(\psi)$ is the gain of an optical filter, and $g(\psi)$ is the gain of optical concentrator. ψ is the angle of incidence. Ψ_c denotes the width of a field of vision at a receiver. The optical concentrator $g(\psi)$ can be given as:

$$g(\psi) = \begin{cases} \frac{n^2}{\sin^2(\Psi_c)} & 0 \le \psi \le \Psi_c \\ 0 & \psi > \Psi_c \end{cases} \tag{11}$$

n denotes the refractive index; $dH_{ref}(0)$ is the channel DC gain on reflection points [5-9] and is given as:

$$dH_{ref}(0) = \begin{cases} \frac{(m+1)A}{2\pi D_1^2 D_2^2} \rho dA_{wall} \cos^m(\varphi)\cos(\alpha)... \\ \quad \times \quad \cos(\beta) T_s(\psi) g(\psi) \cos(\psi), \quad 0 < \psi < \Psi_c \\ 0 \qquad \psi > \Psi_c \end{cases} \tag{12}$$

Where D_1 is the distance between an LED and a reflective point, D_2 is the distance between a reflective point and a receiver, ρ is the reflectance factor, dA_{wall} is a reflective area of small region, α is the angle of incidence to a reflective point, β is the angle of irradiance to the receiver.

With M direct paths from transmitters to a specific receiver and N reflection paths to the same receiver, the total power of the received optical signals is calculated as :

$$P_T = \sum_i^M P_{d,i} + \sum_j^N P_{r,j} \tag{13}$$

Where $P_{d,i}$ is the received optical power of a direct light at the i^{th} point and $P_{r,j}$ means the received optical power of a reflected light at the j^{th} point. M denotes the number of components for direct light and N denotes the number of components for reflected light.

One of the important performance parameter of the communication system is the data transmission rate (DTR) or simply data rate (DR). Usually, the maximum data rate depends mainly on the modulation bandwidths of the components used and the channel impulse response. Due to many reflection components at the walls, the maximum data rate is limited.

At a certain point, the data rate may be higher than the other points because every path of light is different from each other. To develop some general design guidelines for wireless systems, the root-mean-square (RMS) delay spread is used to quantify the multipath channel grossly [31]. Similarly, because the optical signals experience different path lengths, the divided optical signals will arrive at the receiver with different time delay, which causes the intersymbol interference (ISI). The RMS delay spread provides an estimate for a kind of normalized delay time due to multiple reflections. Therefore, the RMS delay spread will be a critical performance criterion for the upper bound of the data transmission rate.
The mean excess delay is defined to be

$$\bar{\tau} = \left(\sum_{i}^{M} P_{d,i} t_{d,i} + \sum_{j}^{N} P_{r,j} t_{r,j} \right) \Big/ P_T \tag{14}$$

$t_{d,i}$ is the consuming time of i^{th} directly light from transmitter to receiver and $t_{r,j}$ is the time of j^{th} reflected light. It can be calculated when we have a transmitter-receiver distance (including a reflection part) and the velocity of light.
The RMS delay spread τ_{RMS} is given by:

$$\tau_{RMS} = \sqrt{\bar{\tau}^2 - (\bar{\tau})^2} \tag{15}$$

Where

$$\bar{\tau}^2 = \left(\sum_{i}^{M} P_{d,i} {t_{d,i}}^2 + \sum_{j}^{N} P_{r,j} {t_{r,j}}^2 \right) \Big/ P_T \tag{16}$$

It is noted that the RMS delay spread depends on the relative levels of optical power components within P_T .

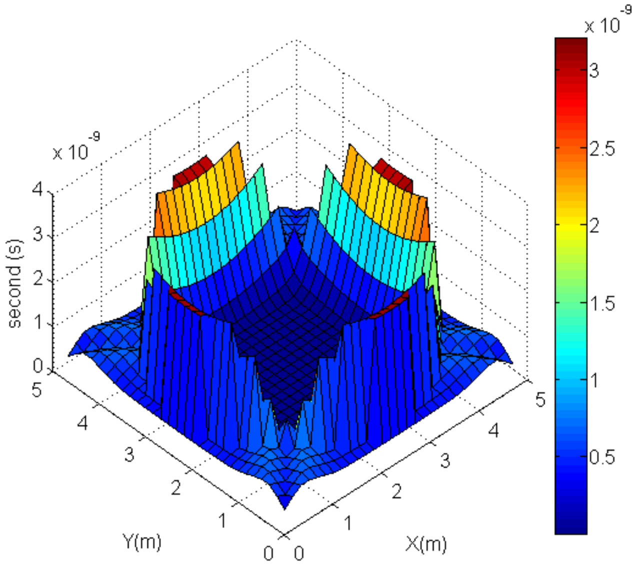

Fig. 10: Distribution of RMS delay spread for one transmitter, position is (2.5, 2.5), semiangle 30 degree.

Fig. 10 shows the distribution of RMS for one transmitter. The maximum value is 3.2 ns (nanosecond); the minimum is 0.86 ps (pico-second).

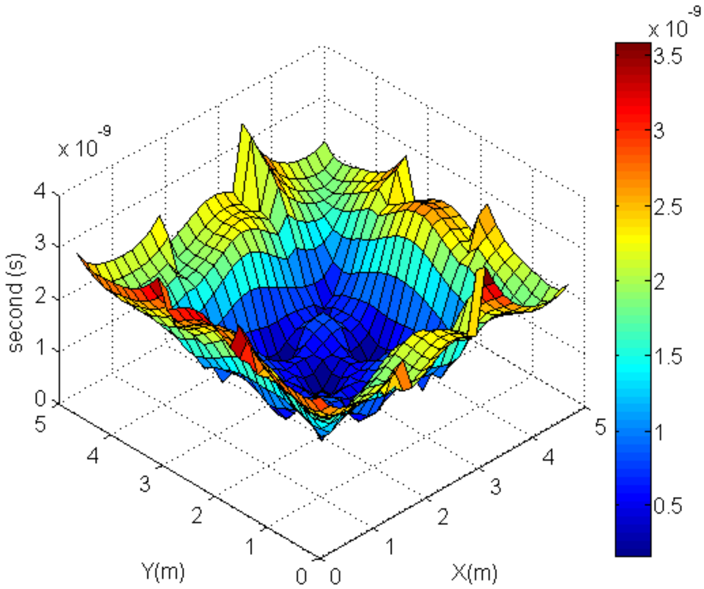

Fig. 11: Distribution of RMS delay spread for four transmitters.
The positions of the transmitters are (1.25, 1.25), (1.25, 3.75), (3.75, 1.25), (3.75, 3.75).
The semi-angle is 30 degree.

Fig. 11 shows the distribution of RMS for one transmitter. The maximum value is 3.57 ns (nanosecond); the minimum is 0.17 ns (nanosecond).

It is accepted that the maximum bit rate that can be transmitted through the channel without needing an equalizer will be limited as follows [31]

$$R_b \leq 1/(10 \times \tau_{RMS}) \tag{17}$$

Usually, the illumination will be installed in some symmetric manners. Also, the configuration is symmetric in the room model. Therefore, it means that there exists redundancy. To avoid calculations of RMS delay spreads in many redundant sample points, we choose sample points for simulation. The one LED transmitter is placed at the center (2.5, 2.5). The positions of four LED lamps are (1.25, 1.25), (1.25, 3.75), (3.75, 1.25), (3.75, 3.75). The values from 1 to 9 in *x*-axes of Fig.12 mean the positions of the receiving points. The list of positions will be show in the table 5.

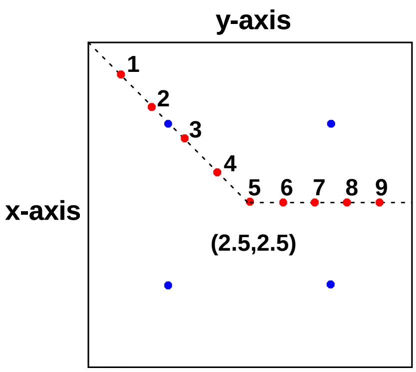

Fig. 12: Configuration for transmitter and receiver. Four blue points denote the positions of four lamps.

The red points denote the receiver points

point	Co-ordinate
1	(0.5,0.5)
2	(1.0,1.0)
3	(1.5,1.5)
4	(2.0,2.0)
5(centre)	(2.5,2.5)
6	(2.5,3.0)
7	(2.5,3.5)
8	(2.5,4.0)
9	(2.5,4.5)

Table 5: Sample points

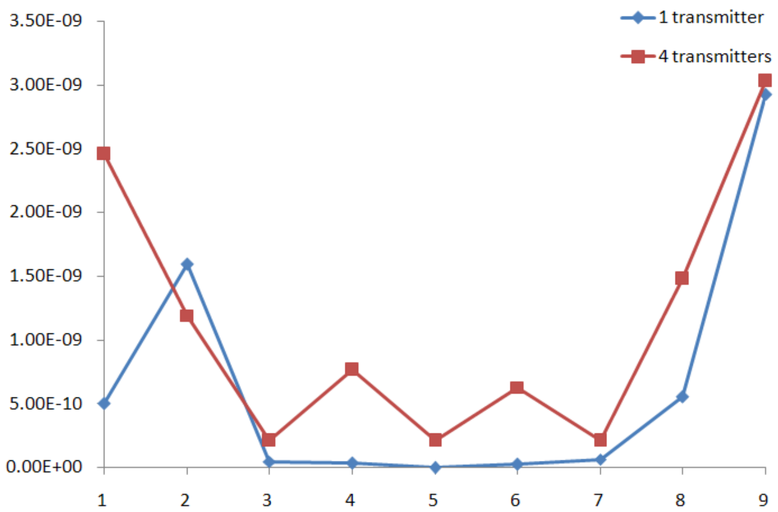

Fig. 13: RMS delay spread at several sample receiver positions.

Fig. 13 shows the RMS delay spread performance at some sample points. The RMS delay spread of system at some specific points in case 4 transmitters usually larger than the value in case 1 transmitter. The main reason is the multipath of light in the system.

4.2 Simulation program: MATLAB and Simulink

In this section, the simulation program is described with the characteristics of MATLAB which is used for the program development.

MATLAB stands for "MATrix LABoratory" and is a numerical computing environment and fourth-generation programming language. Developed by The MathWorks, MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, and FORTRAN.

Simulink is a software package for modeling, simulating, and analyzing dynamical systems. It supports linear and nonlinear systems, modeled in continuous time, sampled time, or a hybrid of the two. Systems can also be multi-rate, i.e., have different parts that are sampled or updated at different rates.

For modeling, Simulink provides a graphical user interface (GUI) for building models as block diagrams, using click-and-drag mouse operations. With this interface, you can draw the models just as you would with pencil and paper (or as most textbooks depict them). Simulink includes a comprehensive block library of sinks, sources, linear and nonlinear components, and connectors. You can also customize and create your own blocks.

Models are hierarchical. This approach provides insight into how a model is organized and how its parts interact. After you define a model, you can simulate it, using a choice of integration methods, either from the Simulink menus or by entering commands in MATLAB's command window. The menus are particularly convenient for interactive work, while the command-line approach is very useful for running a batch of simulations (for example, if you are doing Monte Carlo simulations or want to sweep a parameter across a range of values). Using scopes and other display blocks, you can see the simulation results while the simulation is running. In addition, you can change parameters and immediately see what happens, for "what if" exploration. The simulation results can be put in the MATLAB workspace for post processing and visualization. And because MATLAB and Simulink are integrated, you can simulate, analyze, and revise your models in either environment at any point.

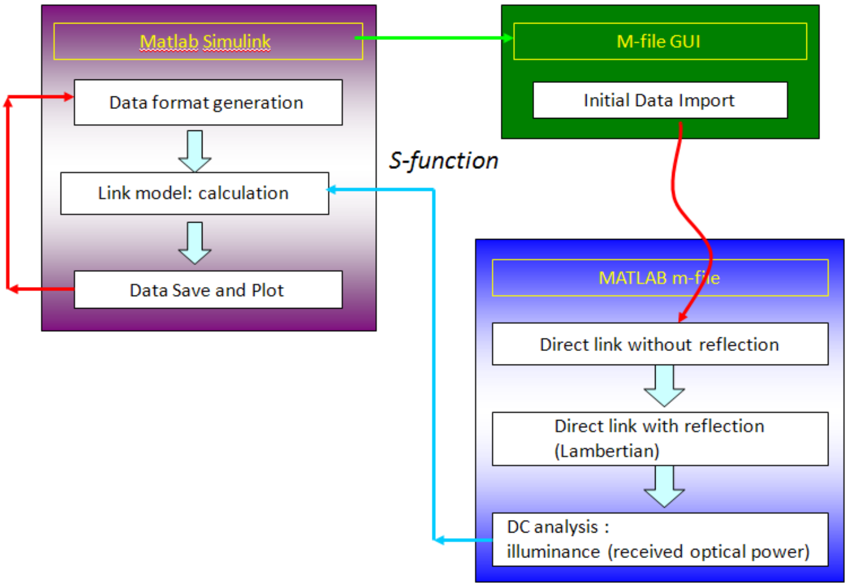

Fig. 14: structure of MATLAB and simulink

Fig. 14 shows the operation of my system for simulating the wireless indoor communication. There is a reciprocal relationship between Simulink, matlab files and interface. Simulink can require input data though interface. The input data are also imported to m-file of matlab. The calculation will be processed by m-file coding and a necessary data can be exported to Simulink. When having enough requirements, Simulink will work properly and give us an expected data.

For making a simulink file, the block diagram is shown in Fig. 15

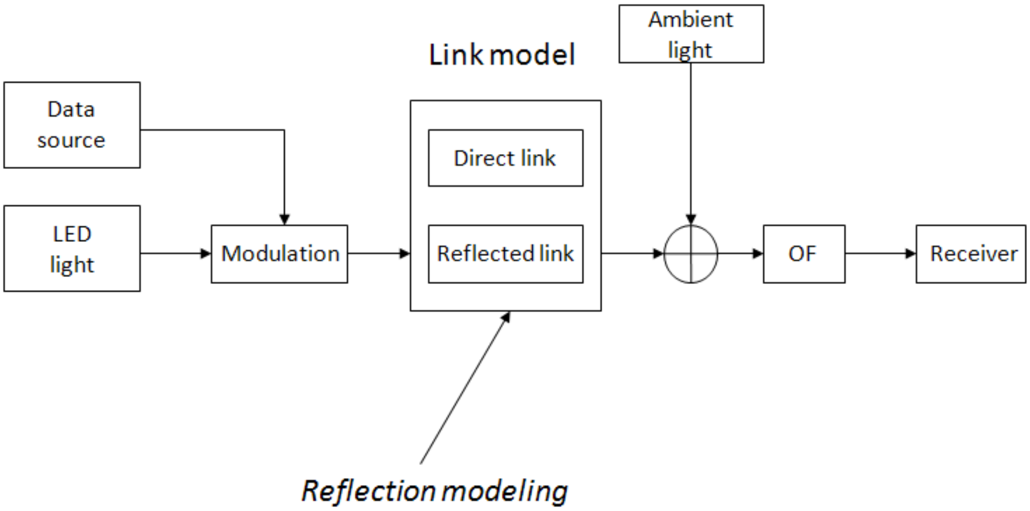

Fig. 15: Simulink model.

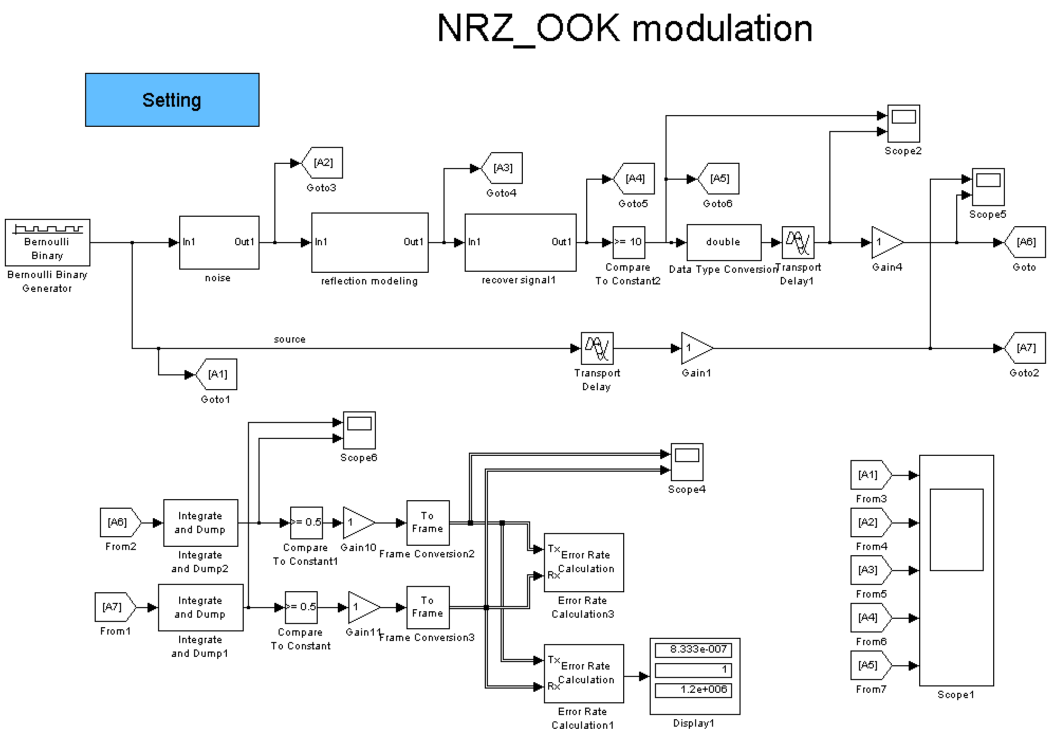

Fig. 16: Detail simulink model for NRZ_OOK modulation format.

Although OOK is basic but it is considerable for assessment of the simulation program for digital transmission. The Fourier analysis of the channel function would be useful. Here, we would like to develop the simulation program for various physical simulation parameters. We assumed a simple example. The parameters like noise, collection area, and filter type are described in Ref. [12-20].

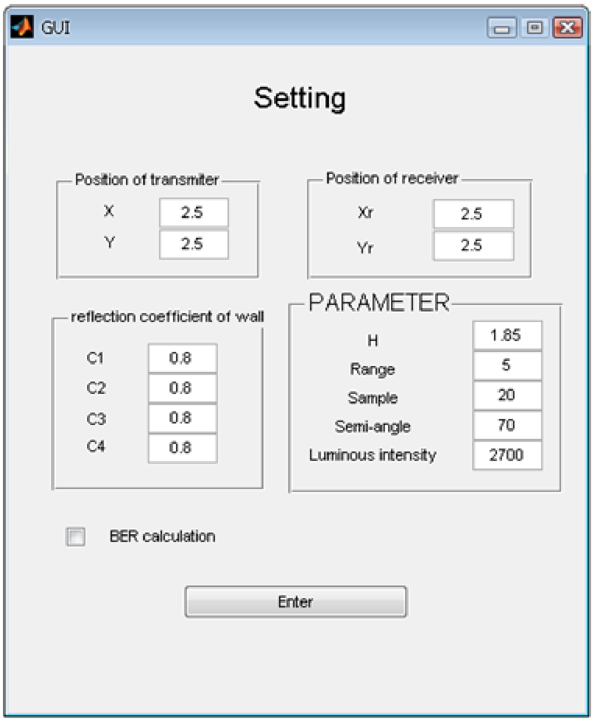

Fig. 17: Graphic User interface (GUI).

Fig. 17 shows the user interface for simulation model. GUI is made by matlab m-file for surveying a changed parameter. Advantages of GUI are shown below:

- Same GUI for all of modulation format.
- Handy for any user and helpful for modifying some parameters.
- Two .txt file will be created by GUI
    - DatafromGUI.txt: For exporting the parameter values for another calculation
    - Choose.txt: For BER calculation

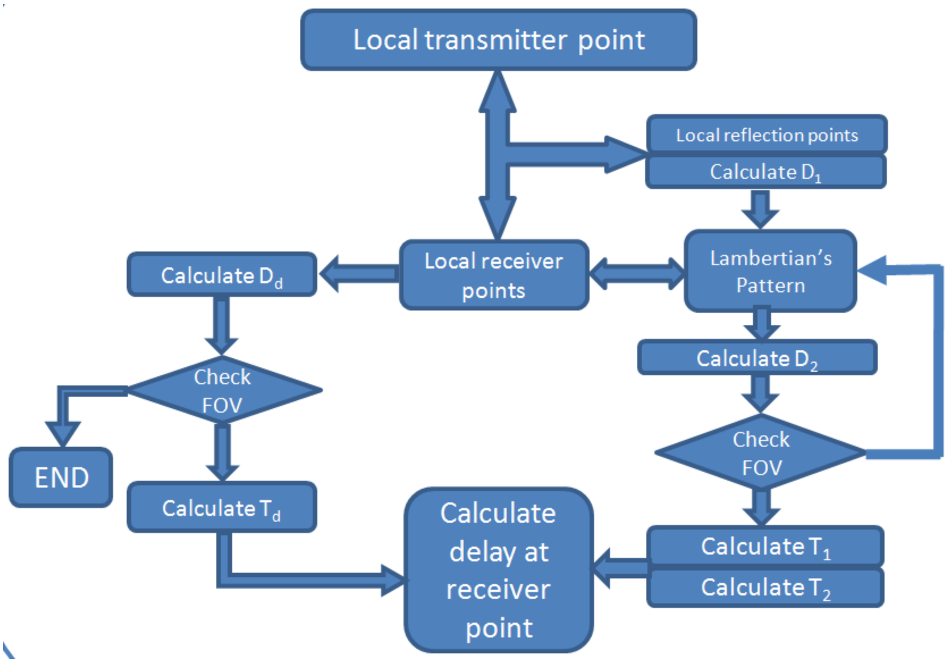

Fig. 18: Delay time calculation.

Fig. 18 shows the way for calculating a time delay at a receiver point in the matlab m-file by using a parameter from GUI. From this, result data can be use for both Simulink and Matlab m-file which calculates the previous RMS delay spread.

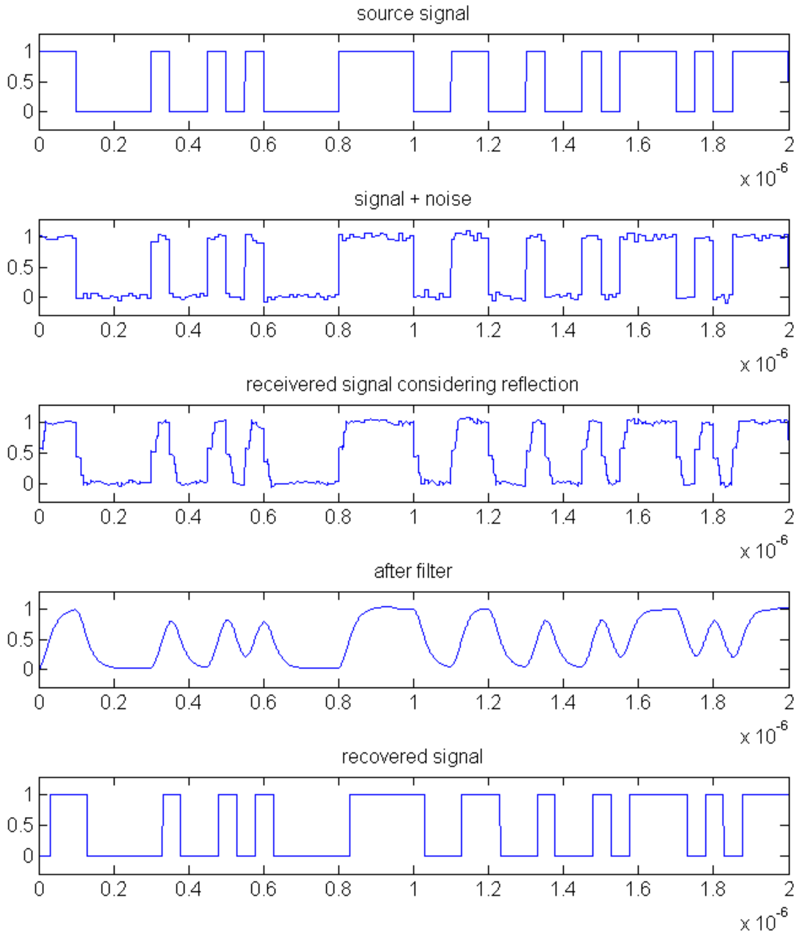

Fig. 19: waveform modulation.

Fig. 19 shows the simulation for NRZ-OOK modulation format using Matlab/simulink. The noise components from ambient light sources are implemented based on the measurements in [39]. The waveform calculation considering reflections with Lambertian pattern at the reflection points are displayed. The simulation program needs to be upgraded by implementing the various physical parameters including the size of active area, the responsivity, the noise components in the photodetectors, the asymmetric reflections on walls, and various advanced modulation formats.

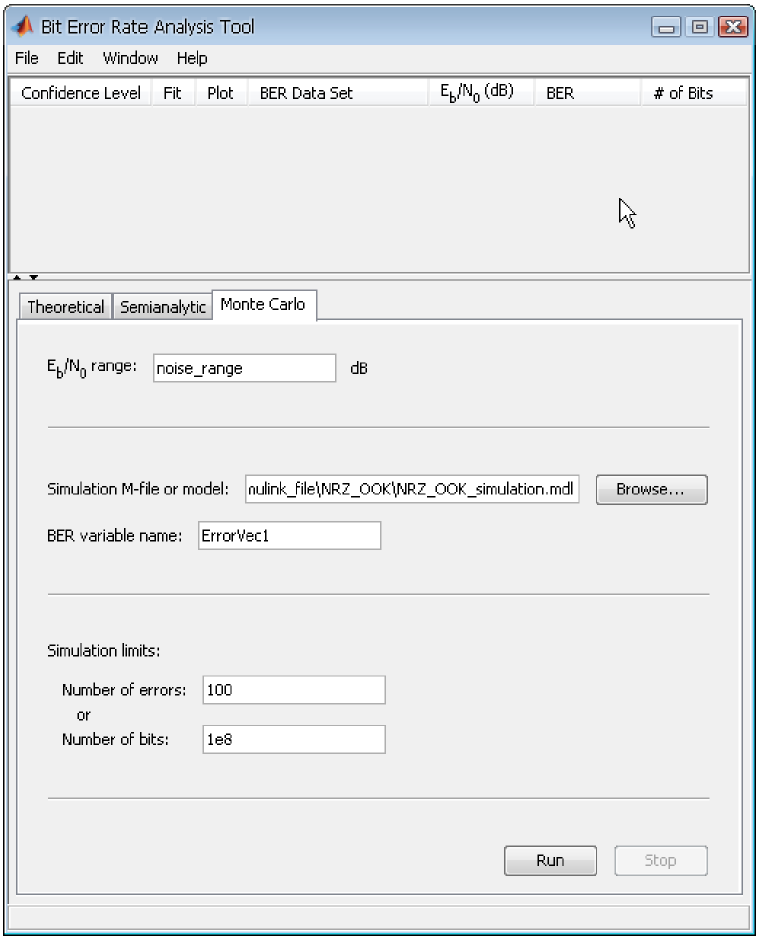

Fig. 20: BERtool or Bit error ratio GUI calculation.

Fig. 20 shows a BERtool which is provide by Communications Toolbox in Matlab. Bertool supports the Bit Error rate calculation by simulink file. Values from Simulink must be imported to Bertool for calculating BER of communication system. BER is one of the goal while simulating communication system.

- Advantage:
  - can see the signal performance
  - more realistic case
- Disadvantage:
  - Taking more time for BER calculation than calculating by coding.

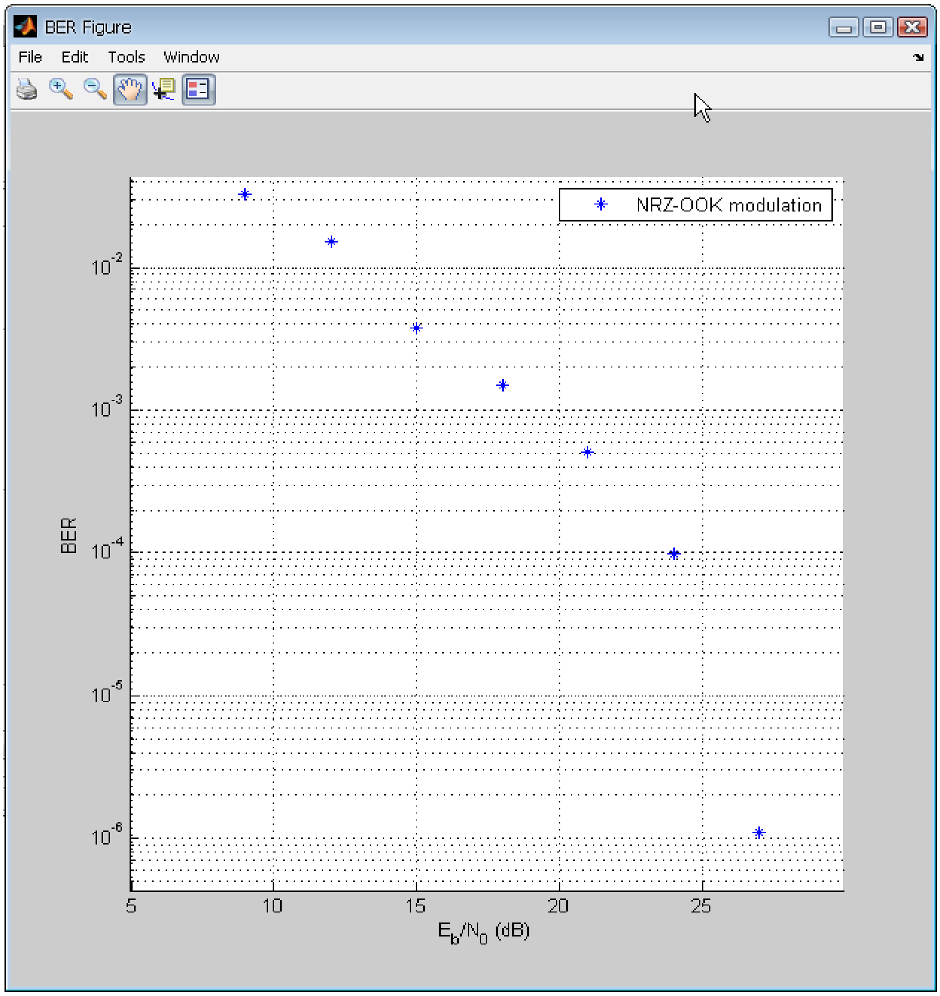

Fig. 21: BER performance.

Fig. 21 shows a result after running BERtool. BER value can be variable depending on E_b/N_o value. E_b/N_o is a normalized signal-to-noise ratio (SNR) measure, also known as the "SNR per bit". Eb/N_o is also exported from Simulink. The value of 10^{-6} is expected for wireless communication.

Chapter 5

CONCLUSIONS

VLC offers the advantage of a communications channel in an unregulated, unlicensed part of the electromagnetic spectrum. In applications where a visible beam is desirable for security it can provide high data rates. There are a number of technical and regulatory challenges to be overcome; rapid technical progress is being made, but the challenges of standardization will require cooperation and agreement from a number of different bodies. However, success brought a low-cost high data-rate infrastructure that can increase wireless capacity substantially. Beside of these, improving the system of wireless indoor using LEDs more and more realistic is one of important goal for widely applications in social living.

In this thesis, I have reported the simulation program for indoor visible light communication environment based on MATLAB and Simulink. The program considered first-order reflections at each wall. Using the simulation program, the distributions of illuminance and RMS delay spread were analyzed at bottom surface. Also, the waveforms for NRZ-OOK have been demonstrated. It is expected to be upgraded with more realistic physical parameters and various advanced modulation formats.

References

1. R. Shorey and B. A. Miller, “The Bluetooth technology: merits and limitations,” in *Proceedings of the 2000 IEEE International Conference on Personal Wireless Communications,* pp.80-84 (17-20 Dec. 2000).

2. http://standards.ieee.org/getieee802.

3. Driggers, Ronald G. (ed.) (2003). *Encyclopedia of Optical Engineering.*

4. J. M. Kahn and J. R. Barry, “Wireless Infrared Communications,” Proc. IEEE **85 (2)**, 265-298 (1997).

5. J. Foerster, “Ultra-Wideband Technology for Short- or Medium-Range Wireless Communications Optical wireless,” Intel Technol. Journal **Q2,** (2001).

6. D. Porcino and W. Hirt, “Ultra-wideband radio technology: potential and challenges ahead,” IEEE Commun. Mag. **41,** 66-74 (2003).

7. D. O'Brien and M. Katz, "Optical wireless communications within fourth-generation wireless systems," J. Opt. Network **4**, 312-322 (2005).

8. J. B. Carruthers, P. Kannan, “Iterative Site-Based Modeling for Wireless Infrared Channels,” IEEE Trans. Antennas and Propag. **50**, 759-765 (2002).

9. M. Kavehrad and S. Jivkova, “Indoor broadband optical wireless communications: optical subsystems designs and their impact on channel characteristics,” IEEE **Wireless Commun. 10,** 30- 35 (2003).

10. J. B. Carruthers, S. M. Carroll, “Statistical impulse response models for indoor optical wireless channels,” Int. J. Commun. Syst. **18,** 267-284 (2005).

11. K. Smitha, A. Sivabalan, J. John, “Estimation of Channel Impulse Response Using Modified Ceiling Bounce Model in Non-Directed Indoor Optical Wireless Systems,” Wireless Pers. Commun. **45,** 1-10 (2008).

12. A. Sivabalan and J. John, "Improved power distribution in diffuse Indoor Optical Wireless systems employing multiple transmitter configurations," Opt. Quantum Electron. **38,** 711-725 (2006).

13. Y. Tanaka, S. Haruyama and M. Nakagawa, “Wireless Optical Transmissions with white colored LED for Wireless home Links,” in *Proceedings of the 11th Int. Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC2000)*, pp.1325-1329 (2000).

14. T. Komine and M. Nakagawa, “Performance evaluation of Visible- Light Wireless Communication System using White LED Lighting,” in *Proceedings of the Ninth IEEE Symposium on Computers and Communications*, pp.258-263 (2004).

15. T. Komine, M. Nakagawa “Fundamental Analysis for Visible Light communication system using LED light,” IEEE Trans. Consum. Electron. **50,** 100-107 (2004).

16. T. Komine, S. Haruyama and M. Nakagawa, “A Study of Shadowing on Indoor Visible-Light Wireless Communication Utilizing Plural White LED Lightings,” Wireless Pers. Commun. **34,** 211-225 (2005).

17. K. Fan, T. Komine, Y. Tanaka, M. Nakagawa, “The Effect of Reflection on Indoor Visible-Light Communication System utilizing White LEDs,” *in Proceedings of the 5th Int. Symposium on Wireless Personal Multimedia Communications (WPMC2002),* pp. 611-615 (2002).

18. T. Komine and M. Nakagawa, “Integrated system of white LED visible light communication and power-line communication,” IEEE Trans. Consum. Electron. **49, 7**1-79 (2003).

19. Y. Tanaka, T. Komine, S. Haruyama and M. Nakagawa, “*Indoor Visible Light Data Transmission System Utilizing White LED Lights*” IEICE Trans. Commun. **E86-B,** 2440-2454 (2003).

20. C. G. Lee, C. S. Park, J.-H. Kim, and D.-H. Kim, “*Experimental verification of optical wireless communication link using high-brightness illumination light-emitting diode* ” Opt. Eng. **46,** 125005 (2007).

21. I. Moreno, M. Avendano-Alejo, R. I. Tzonchev, “*Designing light-emitting diode arrays for uniform near-field irradiance*,” Appl. Opt. **45,** 2265-2272 (2006).

22. I. Moreno, C.-C. Sun, R. Ivanov, “*Far-field condition for light-emitting diode arrays*” Appl. Opt.. **48,** 1190-1197 (2009).

23. H.Yang, J. W. M. Bergmans, T.C.W. Schenk, J-P. M. G. Linnartz, R. Rietman, "*Uniform Illumination Rendering Using an Array of LEDs: A Signal Processing Perspective*" IEEE Trans. Signal Processing. **57,** 1044-1057 (2009).

24. D. W. K. Wong and G. Chen, "*Illumination design of a white light emitting diode wireless transmission system*" Opt. Eng. **46,** 085002 (2007).

25. D. C. O'Brien, "High-speed integrated transceivers for optical wireless," IEEE Commun. Mag. **41,** 58-62 (2003).

26. H. L. Minh, D. C. O'Brien, G. Faulkner, L. Zeng, K. Lee, D. Jung, Y. Oh, "High-Speed Visible Light Communications Using Multiple-Resonant Equalization," IEEE Photon. Technol. Lett. **20,** 1243-1245 (2008).

27. I. Moreno and C.-C. Sun, "Modeling the radiation pattern of LEDs," Opt. Express **16,** 1808-1819 (2008).

28. C.-H. Tsuei, J.-W. Pen, W.-S. Sun, "Simulating the illuminance and the efficiency of the LED and fluorescent lights used in indoor lighting design," Opt. Express **16,** 18692-18701 (2008).

29. E. F. Schubert, *Light-emitting Diodes* (Cambridge University Press, 2006).

30. F. R. Gfeller and U. Bapst, "Wireless In-House Data Communication via Diffuse Infrared Radiation," Proc. IEEE **67,** 1474-1486 (1979)

31. T. S. Rappaport, *Wireless Communications* (Prentice-Hall, 2002)

32. A.Moreira, R.Valadas, and A.Duarte, "*Performance of Infrared Transmission Systems under Ambient Light Interference*" IEE Proc. Optoelecronics, vol. 143, no. 6, Dec. 1996, pp. 339–346.

33. David J.T.Heatley, "*Optical Wireless: The Story So Far*", IEEE Commun. Magazine, December 1998.

34. Grubor, J., Lee, S.C.J., Langer, K.-D., Koonen, T., and Walewski, J.W.: '*Wireless High-Speed Data Transmission with Phosphorescent White-Light LEDs*'. Post deadline session at European Conference on Optical Communications.

35. Le-Minh, H., O'Brien-Dc, Faulkner, G., Zeng, L., Lee, K., Jung, D.J., and Oh, Y.: '*80 Mbit/s Visible Light communications Using Pre-Equalized White LEDs*'. ECOC 2008.

36. Zeng, L., Le-Minh, H., O'Brien, D.C., Lee, K., Jung, D., and Oh, Y.: '*Improvement of Date Rate by using Equalization in an Indoor Visible Light Communication System*'. accepted for presentation at IEEE International Conference on Circuits and Systems for Communications 2008

37. C.Lomba, R.Valadas and A.Duarte, *Safety Issues of the Baseband IR* PHY, Doc. IEEE P802.11— 94/174, 1994.

38. P. Eardley et al., *"Holograms for optical wireless LAN's,"* IEE Proc. Optoelectronics, Special Issue on Free Space Optical Commns, Dec. 1995.

39. A.J.C. Moreira, R.T.Valadas, A.M. de Oliveira Duarte, "*Optical interference produced by artificial light*" Wireless Net., vol. 3, pp. 131-140, 1997.

40. H.Q. Nguyen, J.-H. Choi, M. Kang, Z. Ghassemlooy, D. H. Kim, S.-K. Lim, T.-G. Kang, and C. G. Lee "*A MATLAB-based simulation program for indoor visible light communication environment*" will be presented in The IEEE, IET International Symposium on Communications Systems, Networks and Digital Signal Processing (7th CSNDSP 2010), July 21~23,2010 Newcastle, U.K

41. C.G.Lee et al., final report for ETRI project "*Development of simulation program for indoor visible light communication system*", 2009.

ACKNOWLEDGEMENT

I would like to express my gratitude to my advisor, Prof. Lee Chung Ghiu, for his both insight and broad range of knowledge that he willingly shared with me during the research and writing of my dissertation. His advices are always very helpful, both academically and non-academically. It has been a great pleasure working with him.

I express my appreciation and indebtedness to my friends who co-worked in 2 years of my studying and helped me to adapt new environment: Choi Joon-choi, Jo Eul Byeol, Chang Hyung Joon and Do Ky Son.

I am extremely thankful to my parents and all my family for their love, support, teaching and encouragement in every moment of my life. From the bottom of my heart, I will ever always wish and pray for them.

Nguyen Quang Huy.

저작물 이용 허락서

학과	전자공학과	학번	20087777	과정	석사
성 명	한글 : 응구엔 쾅 후이 영문 : NGUYEN QUANG HUY				
주 소	광주시 동구 지산동 504-8				
연락처	e-mail : quanghuy0584@gmail.com				
논문제목	한글 : 실내용 가시광 통신 시스템 시뮬레이션 연구				
	영문 : SIMULATION OF INDOOR VISIBLE LIGHT COMMUNICATION SYSTEM				

본인이 저작한 위의 저작물에 대하여 다음과 같은 조건 아래 조선대학교가 저작물을 이용할 수 있도록 허락하고 동의합니다.

- 다 음 -

1. 저작물의 DB 구축 및 인터넷을 포함한 정보통신망에의 공개를 위한 저작물의 복제, 기억장치에의 저장, 전송 등을 허락함
2. 위의 목적을 위하여 필요한 범위 내에서의 편집과 형식상의 변경을 허락함(다만, 저작물의 내용변경은 금지함)
3. 배포・전송된 저작물의 영리적 목적을 위한 복제, 저장, 전송 등은 금지함
4. 저작물에 대한 이용기간은 5 년으로 하고, 기간종료 3 개월 이내에 별도의 의사 표시가 없을 경우에는 저작물의 이용기간을 계속 연장함
5. 해당 저작물의 저작권을 타인에게 양도하거나 출판을 허락을 하였을 경우에는 1 개월 이내에 대학에 이를 통보함
6. 조선대학교는 저작물 이용의 허락 이후 해당 저작물로 인하여 발생하는 타인에 의한 권리 침해에 대하여 일체의 법적 책임을 지지 않음
7. 소속 대학의 협정기관에 저작물의 제공 및 인터넷 등 정보통신망을 이용한 저작물의 전송・출력을 허락함

동의여부 : 동의 ( ) 반대 ( )

201 년 월 응구엔 쾅 후이 (인)

조선대학교 총장 귀하

`